Ensemble Assimilation of Doppler Radar Observations

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LONG-TERM GOALS

The final goal of this project is to provide the US Navy with an increased capability of using Doppler radar observations in the detection and prediction of hazardous weather events that usually have a strong randomness in nature and affect the Navy operations, especially over oceans and in remote areas. By developing a high-resolution data assimilation capability that can effectively assimilate Doppler radar observations along with other conventional and remotely-sensed data, the US Navy will have the ability to analyze and forecast the battlespace atmospheric conditions with sufficient detail and accuracy for supporting the Navy mission in threat detection, weapons deployment, and weather safe operations.

OBJECTIVES

The objective of the study is to develop an advanced ensemble-based radar data assimilation system for the US Navy and to address some critical scientific and technique issues associated with ensemble radar data assimilation. The radar data system that will be developed will use flow-dependent background error covariance (instead of the static background error covariance) to account for the complexity and rapid change in the dynamical and microphysical structures inside and outside storms. The system will assimilate all the observed variables from different types of sensors, including Doppler radars, satellites, UASs, and conventional meteorological observations, simultaneously to allow full interactions among the assimilated variables during the data assimilation to keep the balances among the dynamics, thermodynamics and microphysics in the model initial fields. The system will be able to use the observations from many types of radars on different platforms (WSR-88D, DoD meteorological radars and tactical radars both on-land and shipboard, etc.) with an appropriate quality control. Multi-scale data assimilation capability will also be one of the major features of the new radar data assimilation system that allows observational data at different scales to be assimilated concurrently to ensure the scale balance in the ensemble analyses.

APPROACH

The ensemble Kalman filter (EnKF) recently developed at NRL will be the major tool for this study. All the radar data processing and quality control systems previously developed at NRL will be extended to cover the ensemble-based data assimilation and integrated into the EnKF for radar data

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decoding, pre-processing, quality control, bias removal, and observational error estimation. The proposed ensemble radar data assimilation system will assimilate the raw Doppler radial velocity observations directly in the observational space. This will help to reduce the errors induced during the pre-retrieval and interpolation of wind vectors. A data thinning algorithm will also be developed for radar observations to reduce the data density (especially near the radar locations) and hence the data dependency before assimilation. During the last two years, NRL, NSSL and OU have jointly developed a data thinning algorithm for Doppler radial velocity. This algorithm will be further refined and used in the proposed ensemble radar data assimilation system. The NRL 3D Radar Mosaic will serve as the reflectivity data thinning algorithm.

The forward radar observation operators previously developed at NRL for the 3d/3.5d-Var will be adapted for estimating the radar observations in observational space from ensemble forecasts. For storm-scale data assimilation, one of the biggest challenges is the missing storms in the background fields so that there are no estimated radar observations available at observation locations for the data assimilation. The use of ensemble forecasts as the background should have some advantages over the use of a single deterministic forecast in this aspect. But appropriate ensemble spread that covers all the uncertainties of the model forecasts is critical. An adaptive inflation algorithm previously developed for the EnKF will be refined for radar data to assure the appropriate ensemble spread in both the ensemble analyses and forecasts.

Localization is a necessary step in all ensemble-based data assimilation systems to account for the insufficient ensemble size due to the lack of computational power. The length scale of the localization is a very sensitive parameter that affects the ensemble analyses. The assimilation of storm-scale data along with the large- and synoptic-scale observations makes this challenging issue even much more complicated. In this study, we will develop an observation-adaptive, variable-dependent, multi-scale localization algorithm. This algorithm will use a multiple-localization procedure and determine the localization scale based on observational data type, the control variable, and the statistics of the observational and background errors.

Experiments of ensemble radar data assimilation with simulated and real observations will be conducted and the results will be compared with those from the 3d/3.5d-Var. This will help to investigate the impact of the flow-dependent background error covariance on analyses and forecasts. Furthermore, the comparisons between the variational and ensemble-based approaches will also be very useful in the development of a future hybrid radar data assimilation system.

WORK COMPLETED

1. Further improvement in radar data quality control

A new radar-universal QC method for constant power function (CPF) artifacts (sun strobes and bull's eyes) was developed based on the common underlying physics of these artifacts. The method replaces the previous CPF QC algorithm that was tailored only to WSR-88D radar signal characteristics. In addition, two extensions and improvements to previously developed QC methods were completed: (1) The shipboard sea clutter QC algorithm developed in FY11 was further improved and adapted for use with the different scan and data characteristics of NEXRAD radar data. (2) The previous ground clutter QC method for shipboard radar data was enhanced by including model grid terrain height information at the radar data analysis level of the radar DA system (where interpolation of radar data to the model grids is performed). All the new, extended and improved QC methods were successfully

tested on archived data of past QC-category radar case studies and also continuously in real time for the Hazardous Weather Decision Aid (HWDA) project running for Trident Warrior during RIMPAC and Valiant Shield. A new method was also developed at the radar data analysis level to follow the moving ships in order to correctly register their coordinates within the fixed model grids.

2. Real-time demonstration of assimilating shipboard radar observations

In a combined effort of this 6.2 project sponsored by ONR and the 6.4 COAMPS-OS project sponsored by PMW-120, and also in collaboration with Fleet Numerical Meteorology and Oceanography Center (FNMOC) and Space and Naval Warfare Systems Command (SPAWAR) - Pacific, NRL Marine Meteorology Division has developed the Hazardous Weather Decision Aid (HWDA), which has been chosen to participate in the Command and Control focus area of the Trident Warrior fleet experimentation program during the Rim of Pacific (RIMPAC) and Valiant Shield 2012 exercises. HWDA is an automated METOC short-term forecast system based on the NRL Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) – On Demand System (COAMPS-OS®) that concurrently assimilate conventional meteorological and oceanic data with storm observations from shipboard AN/SPS-48E air defense radar Hazardous Weather Detection and Display Capability (HWDDC) and ground-based NEXRAD radars to continuously produce an updated suite of products depicting anticipated atmospheric and oceanographic conditions which are made accessible to the Fleet via the Navy Enterprise Portal - Oceanography (NEP-Oc) Beta website. The data assimilation involves two steps: 1) at hourly intervals, three radar reflectivity data files created by the HWDDC are compressed and automatically transmitted in real-time via SIPRNET to FNMOC; 2) upon receipt at FNMOC, the compressed radar data are decompressed, quality controlled, analyzed, and assimilated along with any available NEXRAD radar data and conventional weather observations within the COAMPS domain. COAMPS-OS then creates two types of forecasts: short-term (0-24 hour) forecast launched on the four synoptic hours (0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC), and very-short-term (0-6 hour) rapid environmental assessment (REA) nowcast launched on the other hours. Each successive REA nowcast has the accumulated benefit of the previous and current hourly radar data updates that feed COAMPS the high-resolution information it needs to better predict the rapidly evolving storm-scale weather systems.

Preliminary HWDDC weather data file transmission tests were successfully conducted on a quasi-continuous basis from December 2011 through to June 2012 prior to RIMPAC, sending data from the USS NIMITZ, USS BONHOMME RICHARD, and USS JOHN C STENNIS to FNMOC, while the necessary COAMPS-OS software was being installed and tested for RIMPAC at FNMOC. History was made when the first ever end-to-end demonstration of the entire system occurred at 2300 UTC, July 12, 2012, when HWDDC weather data from the USS NIMITZ, underway in the RIMPAC operating area, were automatically transmitted to FNMOC; ingested into COAMPS-OS and COAMPS forecasts disseminated to the Fleet through the NEP-Oc Beta website. Results will be shown after the data are declassified.

This demonstration has laid the ground work for potential future Navy operationalization of the assimilation of high-resolution tactical radar data from US Navy ships and Marine units into COAMPS. The resulting forecasts will enhance the warfighter’s environmental awareness and will be invaluable tools to support the planning and execution of Navy ship and aircraft operations at sea and Marine operations ashore.

3. Improvement and testing of NRL ensemble radar data assimilation

Research and development efforts continued to further improve NRL ensemble radar data assimilation system to enhance Navy's capability and accuracy in predicting storms of all scales to support Navy operations and weapon systems. Several technical and scientific accomplishments have been achieved. Some of the studies on radar data assimilation further improve our understanding of radar data and their impact on storm forecasts. Following is a summary of the major scientific accomplishments we achieved in FY12:

1) The algorithms for calculating super-obs and innovation vectors for Doppler radial velocity and reflectivity observations were further improve, tested, and finalized. Now the system is ready for real-time data assimilation. This work provides the observational radar data input to the EnKF for assimilation into COAMPS. Meanwhile, it also makes the radar data available to other NRL existing and future data assimilation systems.
2) The algorithm for Doppler radial velocity data assimilation was extensively tested and further improved. Algorithms were also developed to access the data impact. Larger data impacts were found inside storms than in clear regions outside the storms.
3) Forward observation operator was developed for radar reflectivity observations and integrated into COAMPS EnKF that converts the model forecasts of 3D microphysical fields (q_r, q_s, q_g) from each member of the COAMPS ensemble in model grid space to ensemble estimation of radar reflectivity at observational locations.
4) Radar reflectivity observations were assimilated into COAMPS via EnKF. Preliminary results showed that the impact is relatively small at the beginning, but increases as the forecast time goes.
5) To further understand the impact of reflectivity data on model fields, the innovation vectors were analyzed to investigate the biases and error distributions of radar reflectivity from both ensemble forecast and radar observations. It was found that the model forecasts have large biases, and the error distributions of reflectivity from both the model and observations are far from Gaussian. Algorithms are under development for bias correction and control variable transformation.

RESULTS

1. Improved radar super-obs for data assimilation

The super-obs algorithm for radar observations originally developed by scientists at National Severe Storms Laboratory (NSSL) and implemented at NRL have been further improved and extensively tested. One of the new features added to the algorithm is the filtering of spotty radar pixels in a super-obs box in which most areas are clear. Another new feature of the algorithm is the automatic adaption of COAMPS grid resolution that is used as a reference for the super-obs grid box size. The major new feature added to the algorithm, though, is the ability to estimate the magnitude of errors induced during super-obs that is needed to estimate total observational errors for the data assimilation. Figure 1a gives an example of radar observed Doppler radial velocity and 1b shows the calculated super-obs with a 5 km grid box size from the raw data. It should be pointed out that the data after super-obs are still centered at radar observational grid points without any interpolation. One major advantage of this algorithm is the homogeneous size of super-obs grid boxes throughout the radar domain. To test how

accurately the algorithm works, the super-obs in Fig. 1b are put back to the raw radar data grid points and root-mean-square (RMS) errors are estimated. The results are given in Fig. 1c. By comparing Figs. 1a and 1c, you can find that the algorithm is working as designed. The RMS error induced during the super-obs for this case is 1.01 ms^{-1}.

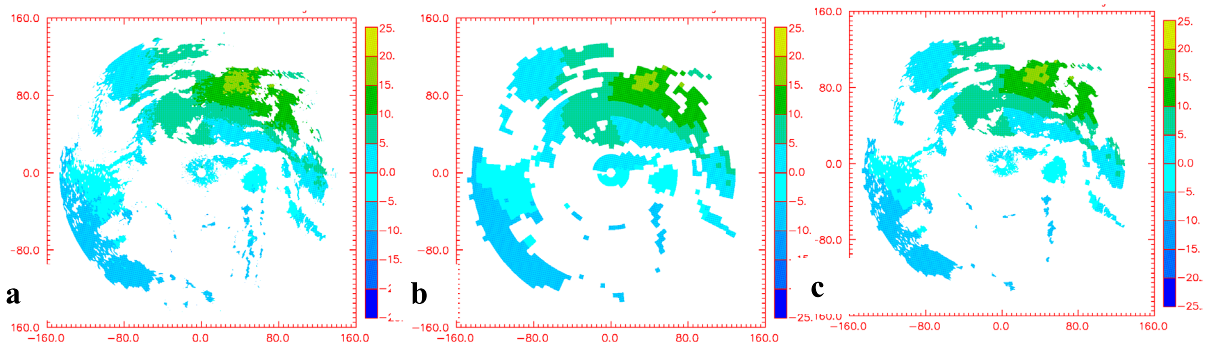

Figure 1. Radar-observed Doppler radial velocity (ms^{-1}) of a storm at 2.4^{o} elevation angle. (a) Raw data, (b) super-obs at 5 km grid box size, and (c) super-obs displayed at radar raw data grid points. The RMS error of V_r induced during super-obs for this case is 1.01 ms^{-1}.

2. Improved storm prediction by ensemble radar data assimilation

a. Improved storm wind forecasts by Doppler radial velocity assimilation

As discussed earlier, the ensemble Doppler radial velocity (V_r) assimilation algorithm has been further improved and extensively tested. The effectiveness of the assimilation of radar wind observations on improving storm prediction was also evaluated. The impact of the data assimilation on the wind forecasts inside storms can be examined by calculating the Doppler radial velocities from the model forecast three-dimensional winds (u, v, w) at radar observational grid points and then comparing them with observed V_r values. RMS errors of the model predicted Doppler radial velocity verified against radar observations are then computed. These scores are calculated at radar observational grid points on a radar conical surface for one scan tilt and then are done tilt by tilt. Figure 2 gives the calculated RMS errors of the forecast Doppler radial velocities from the EnKF experiments with (EnKF-Vr) and without (EnKF) V_r data assimilation, as a function of radar scan elevation angles (in degree), at 00, 03, 06, 09, and 12 forecast hours, respectively. Obviously, V_r data assimilation improves the wind forecasts inside storms remarkably, especially at the beginning of the model forecast. As the forecast time goes on, the impact tends to decrease gradually. At 12 hour forecast time, the impact on wind forecasts becomes marginal.

b. Assimilation of radar reflectivity for improved storm forecasts

Radar reflectivity (Z) observations, after quality control and super-obs, are assimilated into COAMPS by the EnKF to improve storm prediction. Currently, only four model state variables are updated by the data assimilation. They are horizontal winds (u, v), temperature (T), and water vapor mixing ratio (q_v). Update to the model's microphysical fields as well as other model state variables will be added to the EnKF as the research continues. Some preliminary test of the reflectivity data assimilation has been conducted and the validation of the data impact on storm prediction has also been performed using the

same method as stated in previous section. Figure 3 gives RMS errors of Vr forecasts from three EnKF experiments: without radar data assimilation (EnKF), with V_r data assimilation only (EnKF-V_r), and with the assimilation of both V_r and Z, (EnKF-V_rZ). These scores are calculated on the radar conical scan surface with an elevation angle of 3.48 degree and given as a function of forecast lead time. It's interesting to note that the assimilation of reflectivity does not show any positive impact on wind forecasts (compared to EnKF-V_r) at the very beginning. But the impact starts to increase as the forecast time goes on. It reaches maximum at the forecast time of about 9 hours and then keeps basically the same value at 12 forecast hours. This is contradicting to the V_r data assimilation impact (EnKF-V_r) seen in this figure and in Fig. 2 as well. A reasonable explanation of this result is that while the V_r assimilation can directly affect wind forecasts with the impact immediately shown by the reduction in RMS errors, the assimilation of Z has much less direct effect on wind forecasts. Instead, it should have notable the impact on q_v. The change in moisture filed will result in changes in latent heat release, which, in turn through dynamical feedback, affects the wind forecasts. The whole process needs some time to finish. That's probably why we see the delay of the effect of the reflectivity data assimilation on wind forecasts.

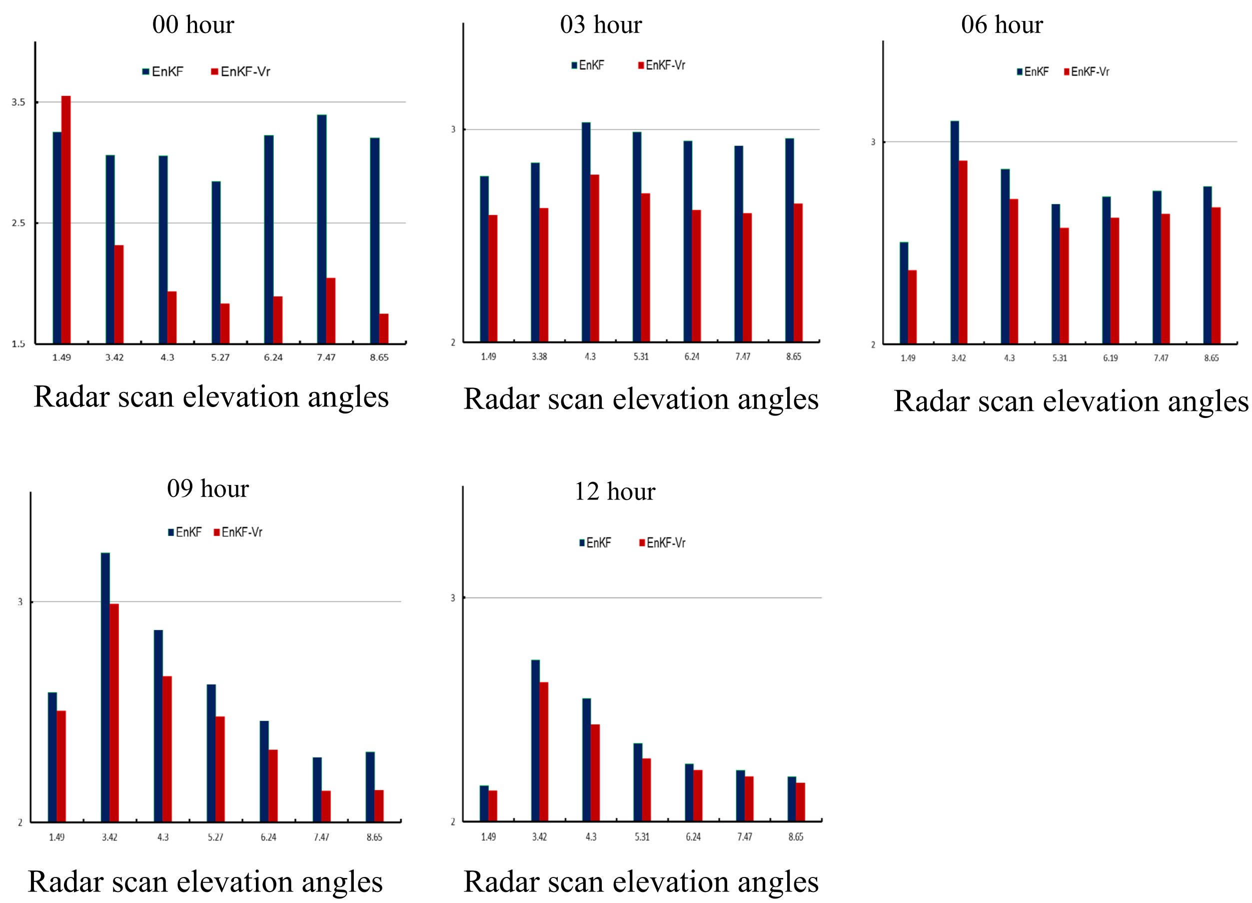

Figure 2. RMS errors of Vr forecasts verified against radar observations as a function of radar scan elevation angle (in degree) at different forecast hours from the EnKF experiments with (EnKF-Vr) and without (EnKF) Vr data assimilation.

24-hour precipitation forecasts from the above three experiments have also been verified against observations. Figures 4a and 4b give the equitable threat scores (EQTS) of the precipitation forecasts for the first and second 24-hour forecast periods, respectively. Again, the assimilation of Z does not show any positive impact in the first 24 hour forecast, but it does in the second 24-hour forecast period.

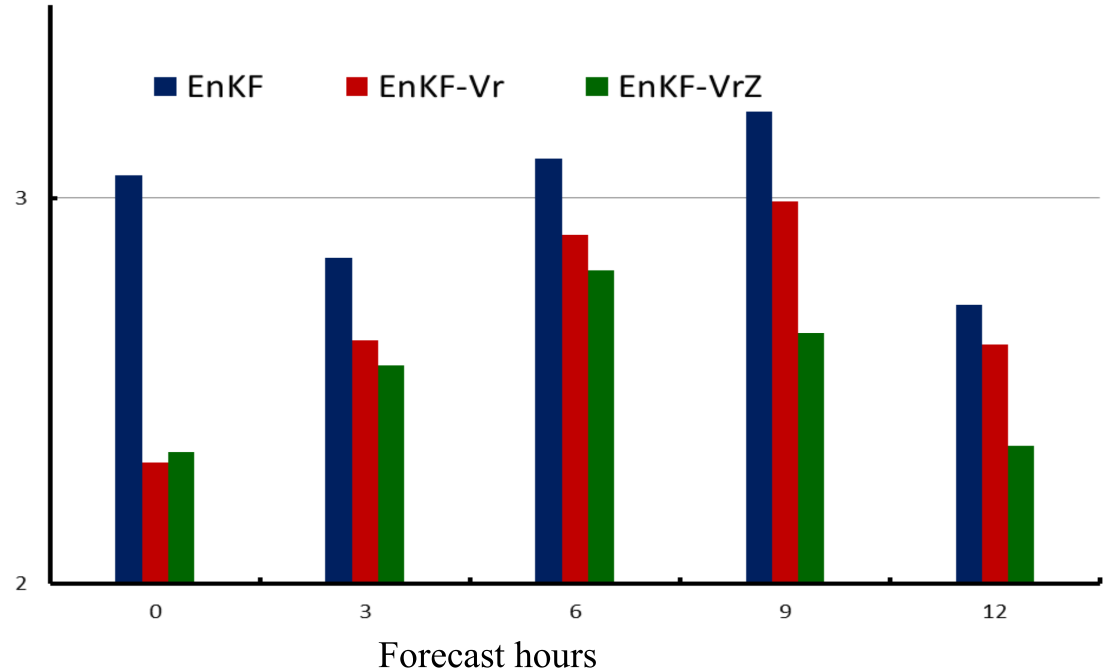

Figure 3. RMS errors of Vr forecasts verified against radar observations at the radar scan elevation angle of 3.42 (degree) as a function of forecast hours from the EnKF experiments of no radar data assimilation (EnKF), Vr data assimilation only (EnKF-Vr), and both Vr and Z data assimilation (EnKF-VrZ).

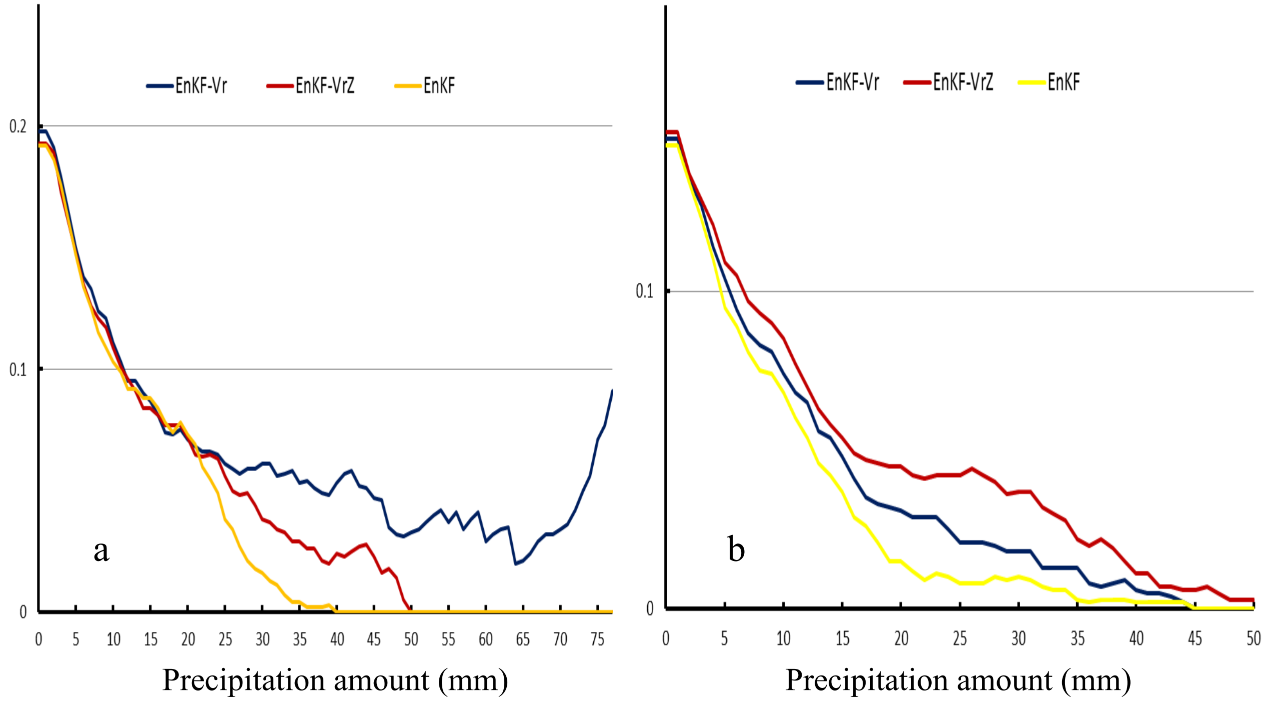

Figure 4. Equitable threat scores of 24-hour accumulated precipitation forecasts verified against precipitation observations for (a) the first and (b) the second 24-hour forecast periods from the EnKF experiments of no radar data assimilation (EnKF), Vr data assimilation only (EnKF-Vr), and both Vr and Z data assimilation (EnKF-VrZ).

IMPACT/APPLICATIONS

Real-time demonstration and several transitions have been made from the efforts of developing NRL radar data processing, quality control and assimilation capabilities. The NRL Doppler Radar Data Processing and Quality Control System is now mature systems for processing real-time radar observations from both S-band and C-band Doppler radars, including the DoD meteorological and tactical radars (such as the land-based Supplemental Weather Radars, or SWR, and shipboard SPS-48E and SPY-1) and those in the WSR-88D Network, with various data formats. These systems also supported the NRL Nowcasting Demo at the Naval Strike and Air Warfare Center (NSAWC) at Fallon, Nevada for providing real-time analyses and nowcasting of weather conditions for Navy pilot training. The Lossless Differential Compression of Weather Doppler Radar Technique significantly compresses the shipboard SPS-48E and SPY-1 Doppler radar UF format data files to ensure the real-time transfer of the full-volume, full-resolution radar observations from ships with limited bandwidth to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) for data assimilation. The software has been transitioned to the Hazardous Weather Detection and Display Capability (HWDDC) and is being installed to the SPS-48E radar systems onboard twelve U.S. Navy aircraft carriers and amphibious assault ships. The newly developed ensemble radar data assimilation system will provide the US Navy with new capabilities of concurrent multi-sensor, multi-scale assimilation of all measurements of the battlespace environment available from conventional and non-conventional meteorological and tactical networks, including those from Doppler radars, into COAMPS with the utilization of multi-scale, flow-dependent background error covariance that accounts for the complex and rapid changes in storm structures.

TRANSITIONS

NRL 3DVAR radar reflectivity along with NRL 3D Radar Mosaic were transitioned to COAMPS-OS running at FNMOC for demonstration of real time assimilation of shipboard radar observations into COAMPS-OS to support RIMPAC and Valiant Shield 2012 exercises.

RELATED PROJECTS

6.4 COAMPS-OS (PMW-120).

PUBLICATIONS

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